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Computational Model of Silicon Carbide JFET Power Device

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Abstract

This paper presents the computation simulation models for silicon carbide (SiC) vertical junction field effect power devices. An analytical, physics based model is capable of accurately replicating the device behavior for the on-off state and transient conditions. The simulation results of the models were validated against measured data obtained from experiments. The current and voltage characteristics of the silicon carbide power device is investigated, the simulation and test results indicate that the switching transient and switching losses are improved compared with the same rated silicon power device. The models developed in this research effort are expected to be valuable tools for power electronic designers in the future.

Keywords- Silicon Carbide;JFET; Computational model; Simulation

1. Introduction

For several decades silicon (Si) has been the preferred material for nearly all semiconductors. Processing of silicon has become very mature and cost efficient. Research on alternative materials is about as old as the application of silicon. In particular so called wide bandgap semiconductors, like gallium nitride GaN and silicon carbide SiC, have very interesting characteristics. In [1], the author indicted the factors of several power semiconductor materials, it shows other wide gap materials have better performance than Si materials in power semiconductor application.

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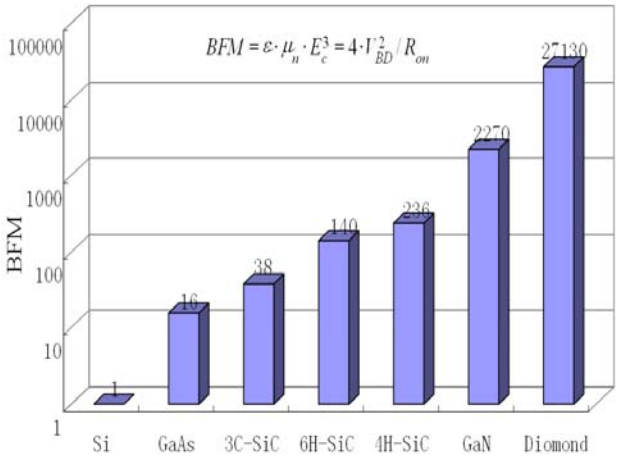

Figure. 1 Performance factor compare of semiconductor materials

For high performance power semiconductors SiC is the preferred choice. Silicon carbide (SiC) semiconductor has the characteristics of wide bandgap (3.0eV for 6H-SiC), higher saturation velocity (2x107cm/s), high thermal conductivity (3.3-4.9 W/cmK), low on resistance (1mΩ/cm2) and high breakdown electric field strength (2.4MV/cm) [1-11]. Therefore, SiC power devices will have the advantages of larger current carrying capability, higher voltage block capability, high operating temperature, and less static and dynamic losses than traditional silicon (Si) power switches. In addition, SiC power devices can operate at higher switching frequencies. Therefore, in a inverter system using SiC power devices, the size of its passive components (inductor and capacitor) can be reduced due to the higher frequency operation, so does the associated heatsinks due to lower losses generated as compared with a conventional Si system. At the present time, it is still difficult to produce SiC MOSFET. SiC JFET, on the other hand, is easier to be manufactured and currently is at engineering stage that is being commercialized. As the manufacture technique improves and its mass production can be realized, it is anticipated that there will be more SiC JFET power switches used in power electronic systems.

For above advantages, the Silicon carbide power devices will be widely used ,in industry, this makes it very important to establish the silicon carbides simulation model for the designers.

2. Simulators and HDLs Model Design

The behavior of semiconductor devices has to be accurately replicated in device models for circuit simulation. Simulation has become an indispensable part of application development as it greatly reduces the time, effort and/or expense required for building and testing circuits. As an example, it is estimated that the model developed at NIST has led to prototyping cost savings in the range of several million dollars. This leads to a faster turn around in production and a cheaper product. Models can be written in various languages. Hardware Description Languages (HDLs) are currently very popular for creating semiconductor models [4]. The models are then simulated in commercially available simulators.

This paper surveys verification and validation of models, especially simulation models in operations research. The validation discusses comparing simulated and real data through simple tests such as graphical and tests, also it discusses testing whether simulated and real responses are positively correlated and moreover have the same mean, using two new statistical procedures based on regression analysis.

Table 1 compares different models, sub circuit model, numerical model and hybrid model in several aspect, such as accuracy, computational efficiency, parameter extraction and development time.

Table 1. Comparison of modeling techniques against various parameters [8]

	ACCURACY	COMPUTATIONAL EFFICIENCY	PARAMETER EXTRACTION	DEVELOPMENT TIME
SUB-CIRCUIT MODELS	AVERAGE	HIGH	AVERAGE	FAST
EMPIRICAL MODELS	AVERAGE	HIGH	AVERAGE	FAST
NUMERICAL MODELS	VERY HIGH	POOR	POOR	SLOW
ANALYTICAL MODELS	HIGH	HIGH	GOOD	AVERAGE
HYBRID MODELS	HIGH	AVERAGE	POOR	SLOW

SPICE is the most popular simulator, the model needs to be written in the C language and includes significant amount of simulator specific details. It is not easy for a modeler to write complex codes in C. Therefore HDLs are widely accepted, as the coding can be done more intuitively. There is no need to include Jacobin entries, matrix stamps or derivative information. Table 4.1 below gives some of the more popular ways in which semiconductor device models are created and their associated simulators.

This effort focuses on creating models for vertical channel JFET like structures in the pspice and computational high level language and simulating it in the pspice and computational simulator. Figure 2 shows the flow chart to get the validated silicon carbide power device simulation model.

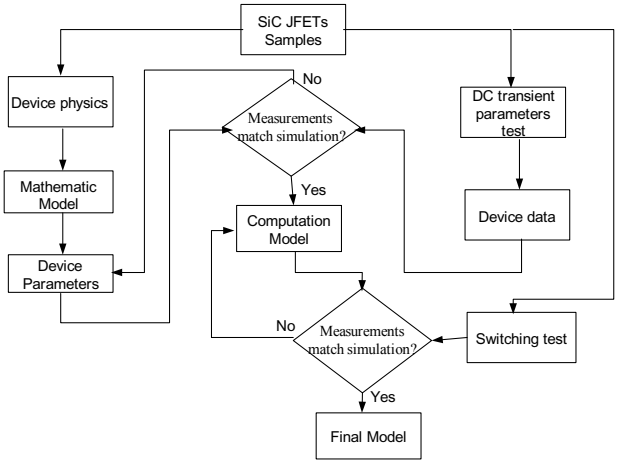

Figure 2. Silicon carbide JFET model flow chart

3. Simulation Analysis

For simulation, some parameters and calculation equation must be derived. Based on semiconductor physics, Different approaches can be used to develop models of power electronic devices [4] . In this model, a voltage controlled current source is used to simulate the current in the JFET channel as shown in equation (2) to (4). Since the main concern is the transient process, the on/off state equations are ignored but the test result is shown.

Assume ε - Dielectric constant of silicon carbide (F/cm),

Vgs - Gate-source voltage (V),

Vds - drain to source voltage ,

Vgs - gate to source voltage,

Ids - drain to source channel current,

Vbi - Built-in junction potential (V),

ND - Base doping density (cm-3),

q - Fundamental electronic charge (C),

Vp - Channel pinch-off voltage (V),

So the depletion width W(x) equation is

$$W(x)=\sqrt{\frac{2\varepsilon\left[V_c(x)+V_G+V_{bi}\right]}{qN_d}} \tag{1}$$

When Pre turn –n, that is $V_{gs} + V_p - V_{bi} \leqslant 0$

$$I_{ds}=0 \tag{2}$$

When in linear area, that is $V_{ds} \leqslant V_{gs} + V_p - V_{bi}$

$$I_{ds}=G_o\left\{V_{ds}-\frac{2}{3}\sqrt{\frac{1}{V_p}}\left[\sqrt{\left(V_{bi}-V_{gs}+V_{ds}\right)^3}-\sqrt{\left(V_{bi}-V_{gs}\right)^3}\right]\right\} \tag{3}$$

G_0 is a extractable parameter.

When in saturation area, that is $V_{ds} \geqslant V_{gs} + V_p - V_{bi}$

$$I_{ds}=\frac{G_oV_p}{3}\left[1-3\frac{V_{bi}-V_{gs}}{V_p}+2\sqrt{\frac{\left(V_{bi}-V_{gs}\right)^3}{V_p}}\right] \tag{4}$$

Using computer language as follow structure, we can get the computation model of silicon carbide power device.

```
template header
header declarations
{
local declarations - must appear first
parameters {
parameter assignments and argument testing
}
netlist components
values {
value assignments
}
control_section {
simulator-dependent control statements
for non-linearities
```

```
}
equations {
 equations describing behavior
 }
 when (expression) {
 event-dependent assignments and scheduling
 }
 }
```

From the semiconductor parameters, the silicon carbide pspice model can be get by following:
.model SiCJFET1 NJF(Beta=0.095 Betatce=0 Rd=0.05 Rs=0.25 Lambda=31.77m Vto=-22 Vtotc=0 Is=10f Isr=0 N=1 Nr=2 Xti=3 Alpha=20.98u Vk=123.7 Cgd=100p M=.5 Pb=1 Fc=.5 Cgs=1000p Kf=50E-18 Af=1)

Using simulation program, the computational model is show in figure 10 and figure 11. the pspice simulation result is shown in figure 3 and figure 4. the result shows the silicon carbide power device has better switching performance than silicon power device.

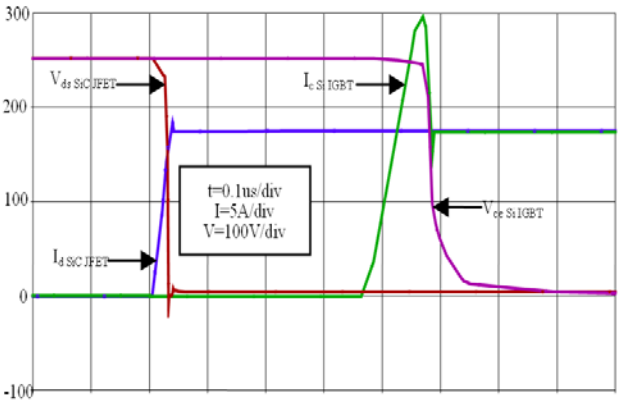

Figure 3. Turn-on waveforms SiC JFET vs. IGBT

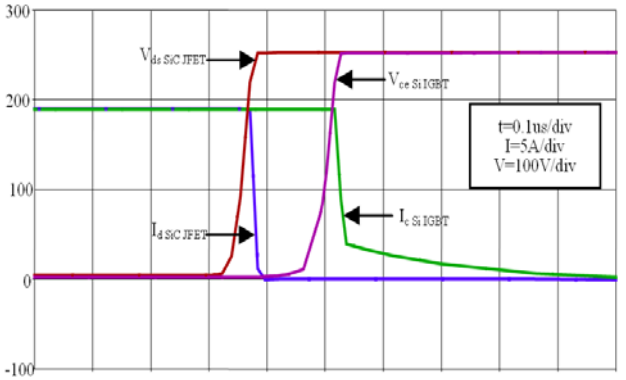

Figure 4. Turn-off waveforms SiC JFET vs. IGBT

4. Experimental Results

Test circuit is established to verify the computational model. Figure 5 shows the switching performance experimental circuit of silicon carbide power device. Figure 6 shows on resistance test result of silicon carbide power device and Figure 7 shows the block voltage characteristic of silicon carbide JFET. Figure 8 shows the turn on waveforms of silicon carbide JFET. Figure 9 shows the turn off waveforms of silicon carbide JFET. Figure 10 shows comparison of computational simulated and experimental turn off voltage Vds results. Figure 11 shows comparison of computational simulated and experimental turn on voltage Vds results.

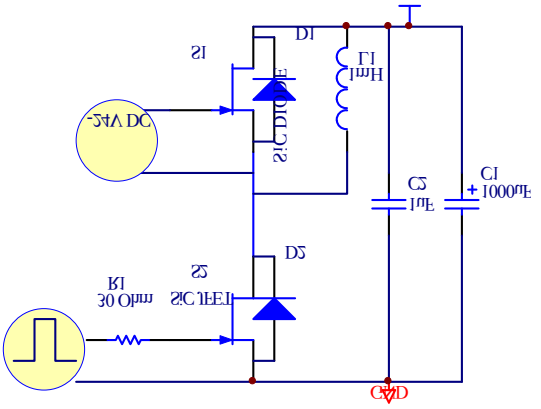

Figure 5. Circuit measuring switching characteristics

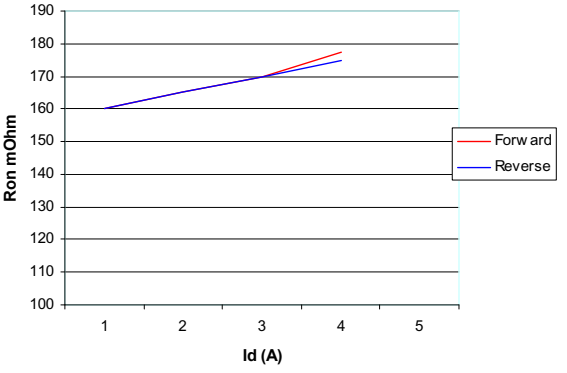

Figure 6 On resistance of SiC JFET

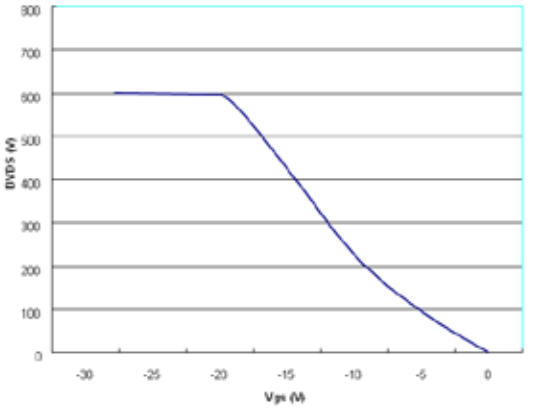

Figure 7 Block voltage Vds vs. Vgs of SiC JFET

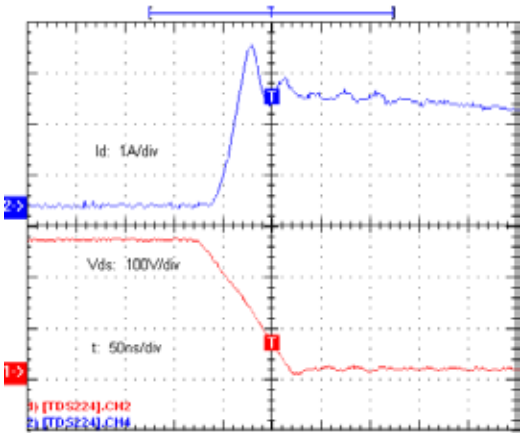

Figure 8. Silicon carbide turn-on waveforms

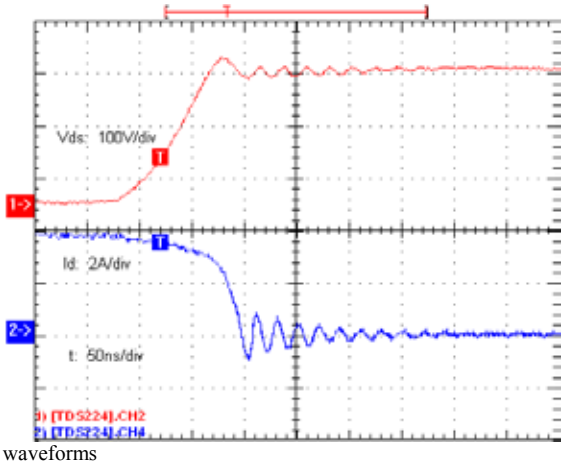

Figure 9. Silicon carbide turn-off waveforms

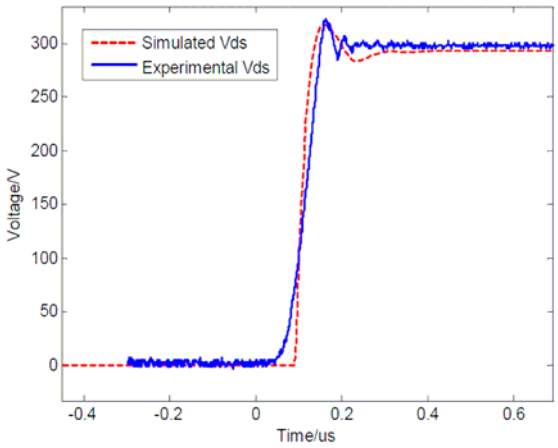

Figure 10. Comparison of computational simulated and experimental turn off voltage Vds results

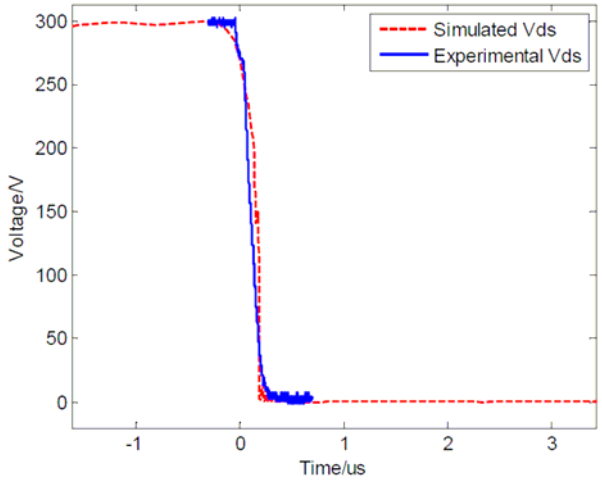

Figure 11. Comparison of computational simulated and experimental turn on voltage Vds results

5. Conclusion

This paper established a computational model of SiC JFET based on test results of the devices. An analytical, physics based model is capable of accurately replicating the device behavior for the on-off state and transient conditions. The simulation results of the models were validated against measured data obtained from experiments. The current and voltage characteristics of the silicon carbide power device is investigated, the simulation and test results indicate that the switching transient and switching losses are improved compared with the same rated silicon power device.

Since higher switching frequency can be easily achieved in silicon carbide JFETs based inverters, a considerable reduction of the size of passive components in solar inverters can be also anticipated. In the next phase of study, high temperature operation up to 300 ^{o}C has also been demonstrated for silicon carbide modules. the operating temperature of the silicon carbide inverter system will be tested. Higher

power rating up to 5kW and later 50kW will be achieved by using parallel connected silicon carbide JFETs. So high temperature operation, relevant thermal packaging and large power ratings will be carried out to demonstrate the merits of SiC JFETs.

Acknowledgment

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